

THE COST OF LIGNOCELLULOSIC SUGAR FOR COMMODITY CHEMICAL PRODUCTION

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ABSTRACT

Currently, some commodity chemicals are produced by microorganisms that convert sugar from corn starch to higher value products. The price of corn is one of the primary economic drivers for these processes. Research on utilization of agricultural byproducts and other types of lignocellulosic biomass as feedstocks for fuel ethanol has been on-going for the last twenty years because biomass can be obtained at a lower cost than corn. Most of the biomass-to-ethanol processes being researched consist of hydrolyzing the biomass' cellulose and hemicellulose to form sugars that are fermented to ethanol. Through the intermediate sugar, biomass can also be a feedstock for other chemicals. The economics of biomass sugar production utilizing dilute acid for hemicellulose hydrolysis and enzymes for cellulose hydrolysis have been analyzed. The analysis includes potential improvements that can reduce the hydrolysis cost making biomass an economically viable feedstock.

INTRODUCTION

A mixed sugar stream is an intermediate in biomass-to-ethanol processes and products other than ethanol could be biologically produced using similar process schemes. The transfer price of biomass sugar has been investigated and ultimately the sugar intermediate stream could compete economically with sugar streams from corn-starch because of lower feedstock costs.

BIOMASS TO ETHANOL PROCESS AND ECONOMICS

For approximately twenty years, the U.S. Department of Energy (DOE) has funded research on the development of renewable, domestically produced fuels for transportation. The biofuels program is one program in this area and it specifically targets transportation fuels made from biomass. The biofuels program is driven by a number of issues including national security, economic competitiveness in the global market, rural economic development, climate change, and air pollution. In the past the program has worked on a varied portfolio of fuel products. The current focus is on fuel grade bioethanol made from the cellulose and hemicellulose components of biomass -- agricultural wastes, trees, grasses, and other lignocellulosic materials. The abundance of biomass makes it a potential low cost feedstock for fuel ethanol and two of its three primary components (cellulose and hemicellulose) can be hydrolyzed into fermentable sugars making a relatively high mass yield (0.35-0.40 lb ethanol / lb biomass) possible. The third primary component, lignin, has other potential uses.

Engineers at the National Renewable Energy Laboratory (NREL) have rigorously analyzed biomass-to-ethanol processes during the life of the program^{1,2} to predict the current and future cost of bioethanol and understand the economic impacts of proposed research. In 1999, a report^{3,4} was published describing the current understanding of process design and economics of a lignocellulosic biomass to ethanol process utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis technology.

Figure 1 is a schematic of the process modeled and reported on in 1999. Hardwood sawdust enters the process and is pretreated at elevated temperatures with a sulfuric acid catalyst to hydrolyze the hemicellulose into sugars. Sugars released from the hemicellulose include xylose, arabinose, galactose, and mannose. Pretreatment not only hydrolyzes the hemicellulose sugars, but it also makes cellulose more

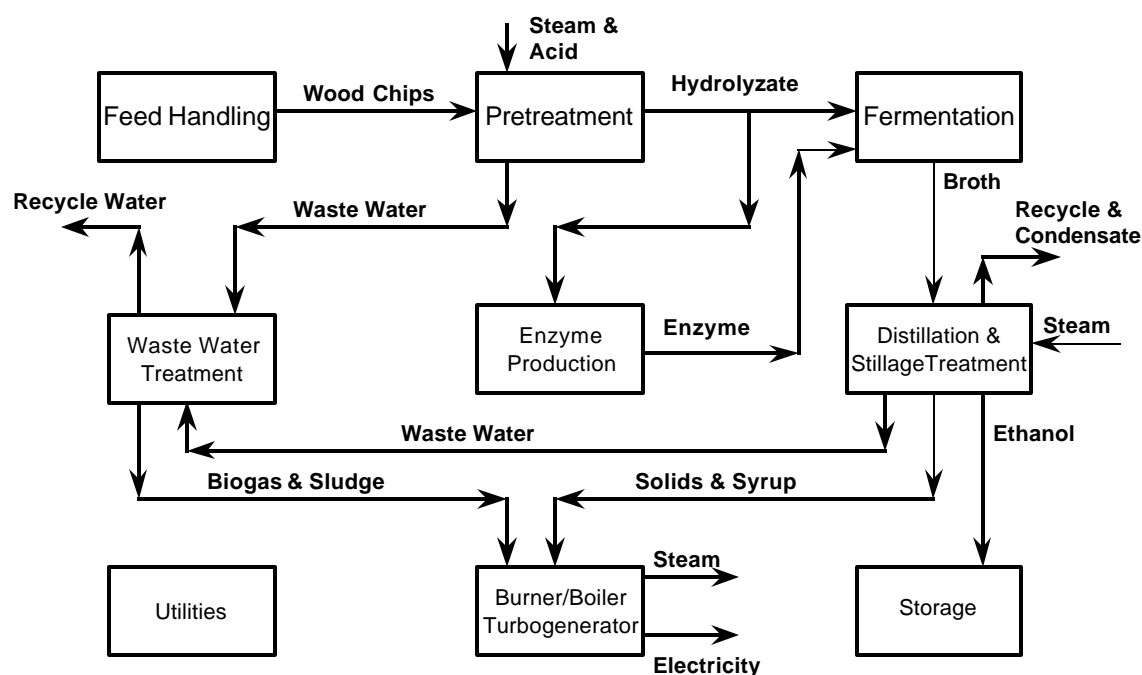


Figure 1. Schematic of One Biomass-to-Ethanol Process

accessible to enzymatic hydrolysis. Approximately five percent of the pretreated slurry (hydrolyzate) is pumped to enzyme production where cellulase enzymes are biologically produced by fungi in submerged culture reactors. The remaining 95% of the hydrolyzate is pumped to fermentation where the cellulase enzyme broth and ethanologens are added. This area's process scheme is called simultaneous saccharification and co-fermentation (SSCF) because cellulase enzymes are hydrolyzing cellulose into glucose and that glucose is immediately consumed by ethanologens to produce ethanol. Genetically modified ethanologens are utilized because they are capable of simultaneously converting both glucose and sugars from hemicellulose. After fermentation the ethanol broth is distilled and dehydrated to fuel grade ethanol that is stored and sold as the primary product. Lignin-rich solids from distillation are sent to the burner/boiler/turbogenerator area where they are dried and burnt to produce steam and electricity for the process. Any excess electricity is sold to the local power grid. Wastewater from the distillation area is pumped to wastewater treatment where it is mixed with flash vapor from the pretreatment area. Wastewater treatment produces a clean water stream for recycling and biogas and sludge that can be burnt to produce steam and electricity. Utility equipment to support the process is included in the model.

To determine the economics of the above process, parameter sets were developed for different time periods ranging from technology that should be available in the near term to technology with a predicted availability of 2015 if research continues. Material and energy balances were calculated for each case and stream results were utilized for equipment sizing. Total capital investments were determined from the equipment costs (involving n^{th} plant assumptions) and operating costs were calculated from stream flow rates. Finally, minimum ethanol selling prices were calculated from the total capital investment and operating costs with a 10% post-tax discounted cash flow rate of return. The minimum ethanol selling prices range from \$1.44/gal (near-term NREL technology) to \$0.76/gal (2015 technology).

PRODUCTION OF BIOMASS SUGARS

Sugars are an intermediate product in the formation of ethanol. Hemicellulose is hydrolyzed to form xylose, arabinose, galactose, and mannose in the pretreatment area. Cellulase enzyme saccharifies the cellulose into glucose in the fermentation area. Two potential process schemes for other products follow: first, organisms other than ethanologens could consume the sugars and produce a desirable product or group of products simultaneously with saccharification and, second, enzymatic hydrolysis could be operated in a near sterile way producing a transferable sugar stream as its product.

To analyze the cost of the intermediate sugar stream the second scheme was chosen so the following areas were removed from the biomass-to-ethanol process model and economics: wastewater treatment (a cost was kept for treatment of the pretreatment flash vapor), distillation and stillage treatment, and storage. The fermentation area was converted to an enzymatic hydrolysis area by removing seed production of the ethanologen. Finally, a counter-current washer was added after the hydrolysis area to separate lignin for combustion in the burner from the dilute mixed sugar stream. Mass balances and capital and operating costs were determined for the sugar process and the minimum sugar transfer price was calculated.

Five cases were modeled at feedstock costs of \$25/dry ton and their results are presented in Figure 2. The base case, resulting in a minimum sugar transfer price of 7.5¢/lb, is based on parameters that are believed to be achievable soon with current research. If pretreatment yields and enzyme productivity can be improved to levels claimed possible by some researchers, the minimum transfer price will be reduced to 6.6¢/lb as shown in the potential near term case. By 2005, protein engineering is expected to result in a three-fold improvement of the enzyme specific activity and increased thermo-tolerance. Combining the protein engineering based improvements with the potential near term parameters reduces the minimum transfer price to 5.2¢/lb. By 2010, more protein engineering is expected to result in a ten-fold improvement in the enzyme specific activity from current levels. That improvement is estimated to further reduce the

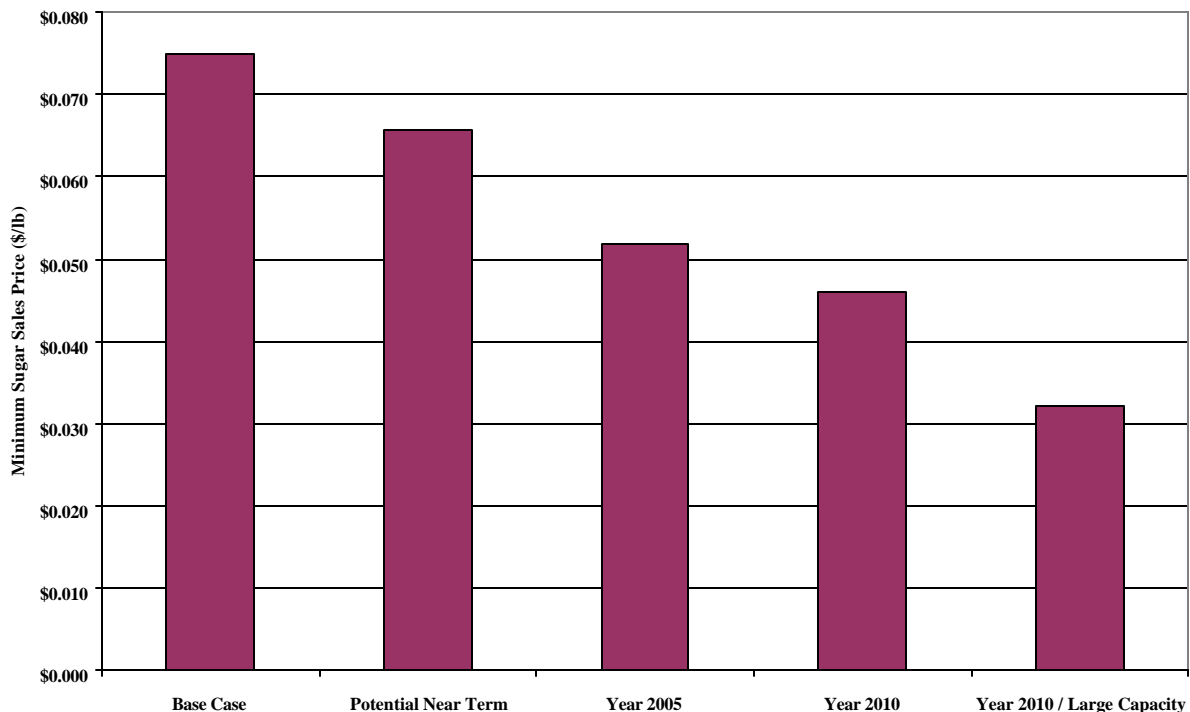


Figure 2. Estimated Biomass Sugar Transfer Prices

minimum transfer price to 4.6¢/lb. A feedstock collection infrastructure may also be in place by 2010 allowing much larger plant sizes. By increasing the plant feed rate from 2000 dry tonne/day to 10,000 dry tonne/day, the minimum selling price is reduced from 4.6¢/lb to 3.2¢/lb.

In some cases the lignin stream can be sold either to a nearby plant that converts lignin into higher value byproducts or a larger more cost-efficient biomass power facility. Selling the lignin at the same price as the feedstock (on a lower heating value basis) reduces the sugar price by 1.1¢/lb in the base case and 0.3¢/lb in the 2010 / Large Capacity case.

SUMMARY

By removing the ethanol specific portions of a biomass-to-ethanol process model, an economic analysis of a mixed sugar stream from biomass has been developed. The analysis shows that a dilute mixed-sugar stream from biomass is estimated to carry a required transfer price of 7.5¢/lb in the near-term and can be reduced to 3.2¢/lb with continued research and industry development. That research needs to involve improved pretreatment yields as well as increase cellulase specific activity and thermotolerance. If the lignin stream can be sold, the sugar transfer price can be reduced by 1.1¢/lb in the base case and 0.3¢/lb in the 2010 / Large Capacity case.

ACKNOWLEDGEMENT

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¹ Wright, J.; D'Agincourt, C. Evaluation of Sulfuric Acid Hydrolysis Processes for Alcohol Fuel Production. *Biotechnol. Bioeng. Symp. No. 14*, **1984**, 105-123.

² Hinman, N. D.; Schell, D. J.; Riley, C. J.; Bergeron, P. W.; Walter, P. J. Preliminary Estimate of the Cost of Ethanol Production for SSF Technology. *Appl. Biochem. Biotechnol.* **1992**, 34/35, 639-649.

³ Wooley, R.J.; Ruth, M.; Sheehan, J.; Majdeski, H.; Galvez, A. Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis Current and Futuristic Scenarios; Report No. NREL/TP-580-2615. National Renewable Energy Laboratory, Golden, CO, July 1999, (http://www.ott.doe.gov/biofuels/process_engineering.html).

⁴ Wooley, R.; Ruth, M.; Glassner, D.; Sheehan, J. Process Design and Costing of Bioethanol Technology: A Tool for Determining the Status and Direction of Research and Development. *Biotechnol. Prog.* **1999**, 15, 794-803.



The Potential Cost of Lignocellulosic Sugar for Commodity Chemical Production

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Biomass-to-Ethanol Background

- DOE's Biofuels Program has Funded Biomass-to-Ethanol Research for over 20 years
 - Lignocellulosic Biomass is Abundant and Inexpensive
 - Agricultural Residues, Wood and Paper Waste, and Energy Crops
 - Composed Primarily of Cellulose, Hemicellulose, and Lignin

Biomass-to-Ethanol Background

- Production of Other Commodity Chemicals in “Biorefinery” can Assist in Making Bioethanol Economically Viable
- Pentose and Hexose Sugars are a Natural Intermediate in Bio-ethanol Production

Potential Higher Value Products from Sugars

	Market MM lb/yr	Price \$/lb	Yield lb/ton	Fraction of Market**	Revenue*** MM\$/yr
Ethanol*	82,000	\$0.12	527	0.4%	\$ 44
Acetic Acid	5,300	\$0.38	574	8%	\$ 153
Adipic Acid	2,000	\$0.70	860	30%	\$ 421
Butanol	1,800	\$0.50	287	11%	\$ 100
Acrylic Acid	1,500	\$0.87	918	43%	\$ 559
Propylene Glycol	1,000	\$0.60	310	22%	\$ 130
Citric Acid	460	\$0.75	998	152%	\$ 345
Glycerol	380	\$0.90	574	106%	\$ 342
Propionic Acid	220	\$0.44	528	168%	\$ 97
Malic Acid	18	\$0.81	642	2497%	\$ 15

* Assuming 10% of Gasoline Market

** Based on One 2000 dry ton / day Facility

*** Based on One 2000 dry ton / day Facility or 100% of Market

Biomass-to-Ethanol Process with Dilute Acid Pretreatment and SSCF

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graph LR; FH[Feed Handling] -- "Wood Chips" --> P[Pretreatment]; P -- "Steam & Acid" --> P; P -- "Hydrolyzate" --> F[Fermentation]; P -- "Waste Water" --> WWT[Waste Water Treatment]; F -- "Broth" --> DST[Distillation & Stillage Treatment]; DST -- "Recycle & Condensate" --> F; DST -- "Steam" --> DST; DST -- "Ethanol" --> S[Storage]; P -- "Enzyme" --> EP[Enzyme Production]; EP -- "Enzyme" --> F; DST -- "Solids & Syrup" --> BBT[Burner/Boiler Turbogenerator]; WWT -- "Biogas & Sludge" --> BBT; BBT -- "Steam" --> BBT; BBT -- "Electricity" --> BBT; BBT -- "Waste Water" --> WWT; WWT -- "Recycle Water" --> P;
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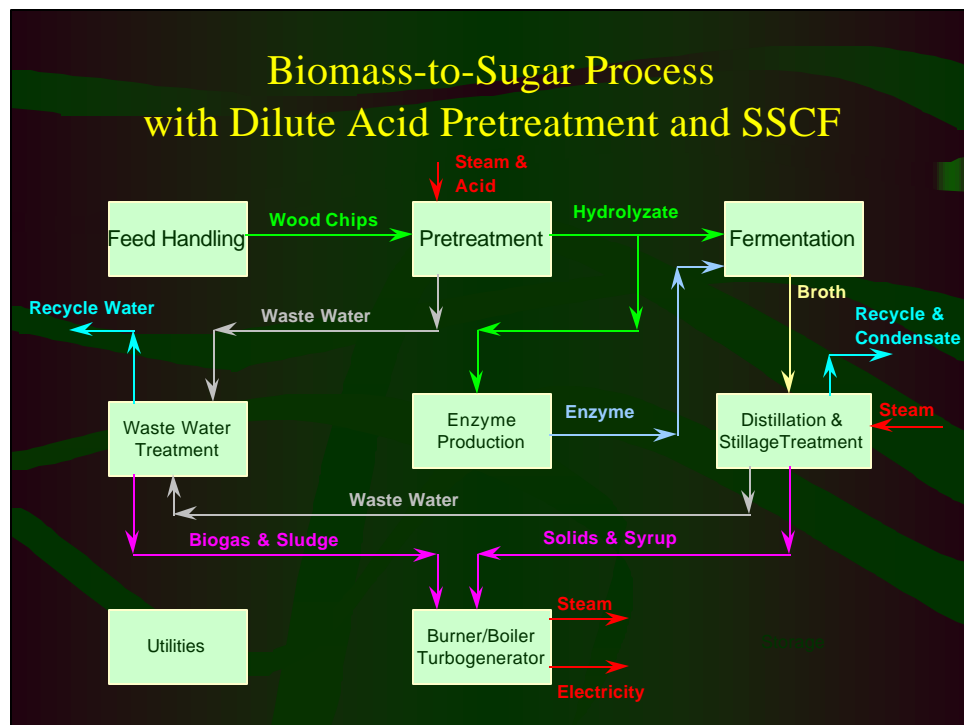
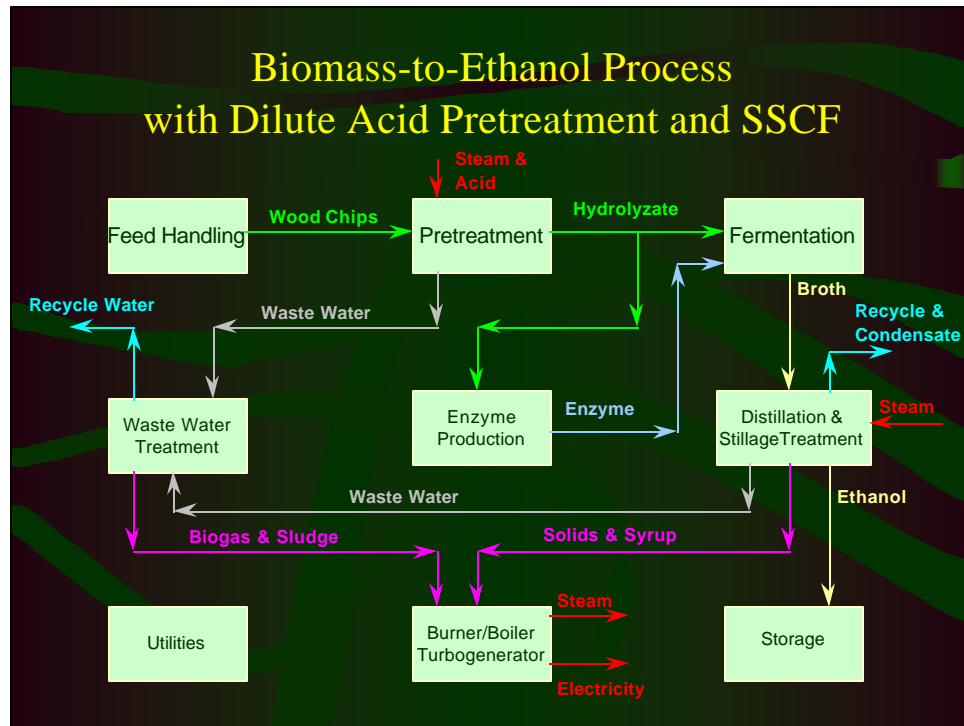
The diagram illustrates the Biomass-to-Ethanol Process with Dilute Acid Pretreatment and SSCF. The process flow is as follows:

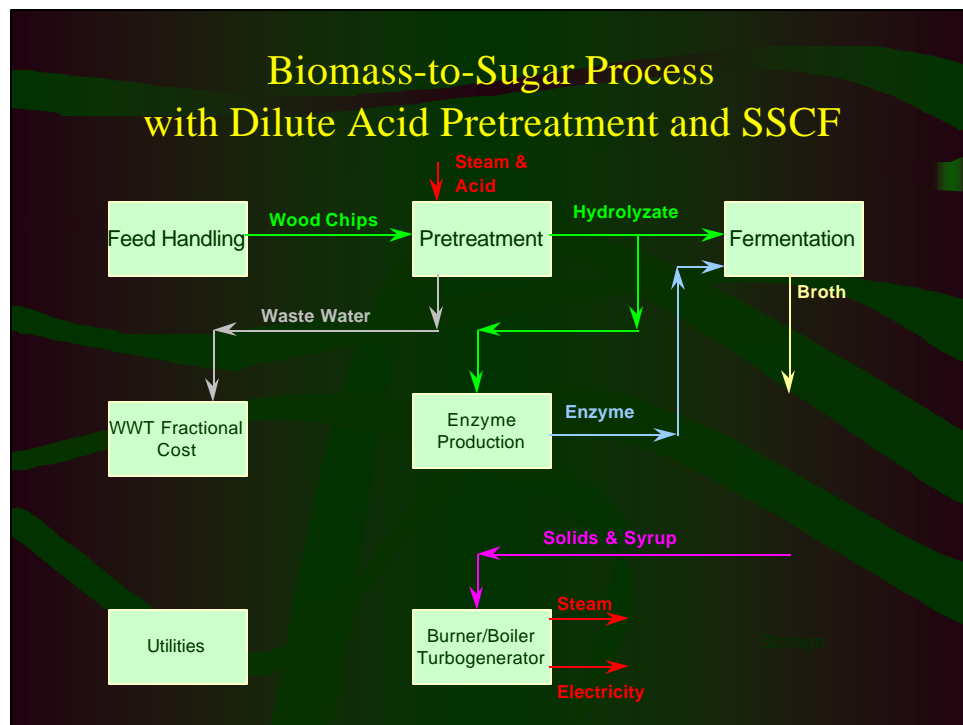
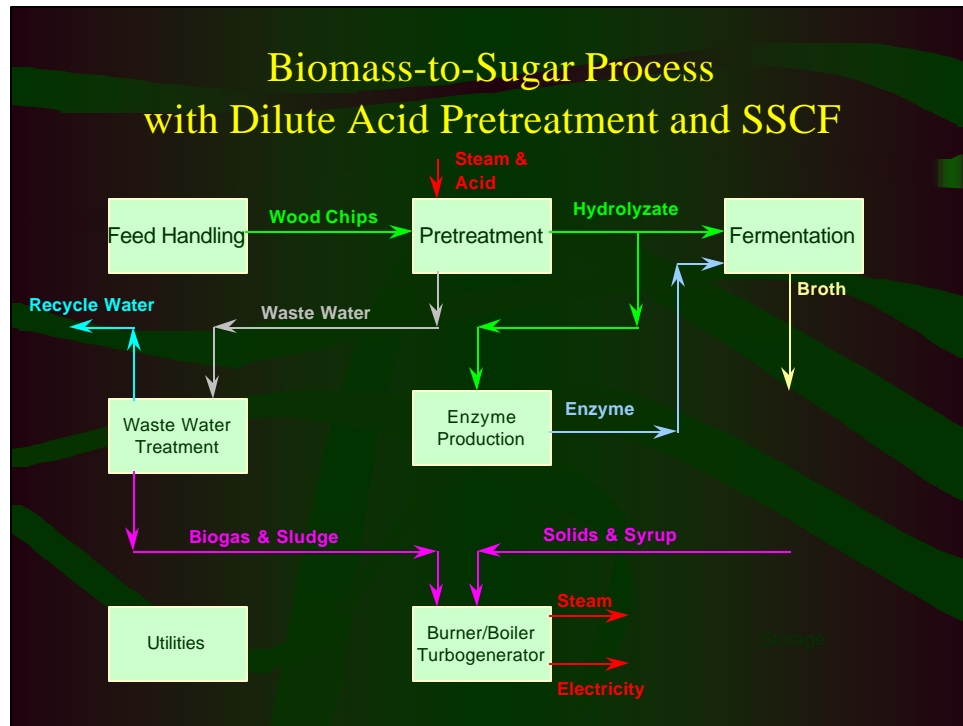
- Feed Handling** provides **Wood Chips** to **Pretreatment**.
- Pretreatment** receives **Steam & Acid** and produces **Hydrolyzate** for **Fermentation**.
- Pretreatment** also produces **Waste Water**, which is sent to **Waste Water Treatment**.
- Fermentation** receives **Hydrolyzate** and produces **Broth** for **Distillation & Stillage Treatment**.
- Distillation & Stillage Treatment** receives **Broth** and produces **Recycle & Condensate** for **Fermentation**.
- Distillation & Stillage Treatment** also produces **Steam** and **Ethanol** for **Storage**.
- Distillation & Stillage Treatment** produces **Solids & Syrup** for the **Burner/Boiler Turbogenerator**.
- Waste Water Treatment** produces **Biogas & Sludge** for the **Burner/Boiler Turbogenerator**.
- Waste Water Treatment** also produces **Recycle Water** for **Pretreatment**.
- Burner/Boiler Turbogenerator** produces **Steam** and **Electricity**.
- Burner/Boiler Turbogenerator** also produces **Waste Water** for **Waste Water Treatment**.

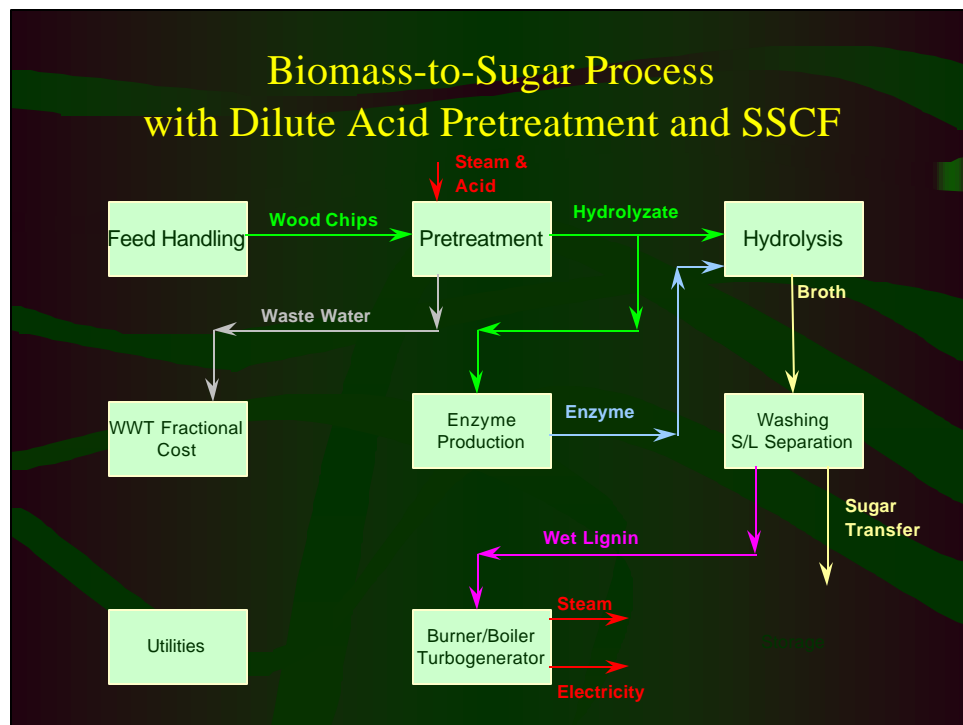
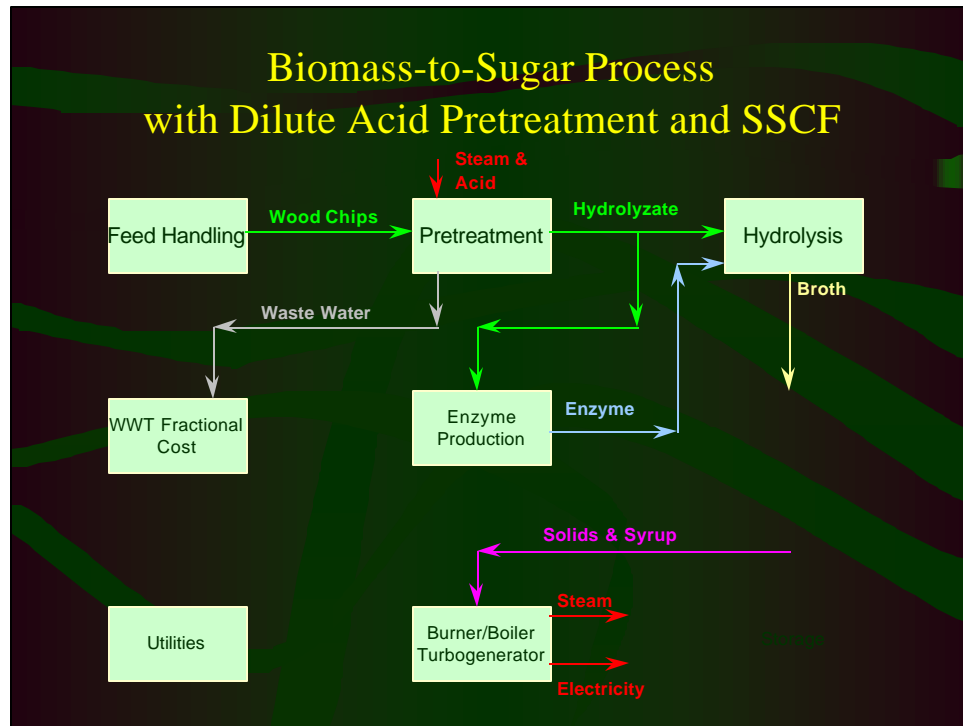
Biomass-to-Ethanol Economic Analysis

- Estimate Parameters for Several Cases
- Calculate Material and Energy Balances
- Determine Capital and Operating Costs
- Calculate Minimum Ethanol Selling Price
 - Base Case -- \$1.44/gal
 - Potential Near Term -- \$1.16/gal
 - 2005 -- \$0.94/gal
 - 2010 -- \$0.82/gal

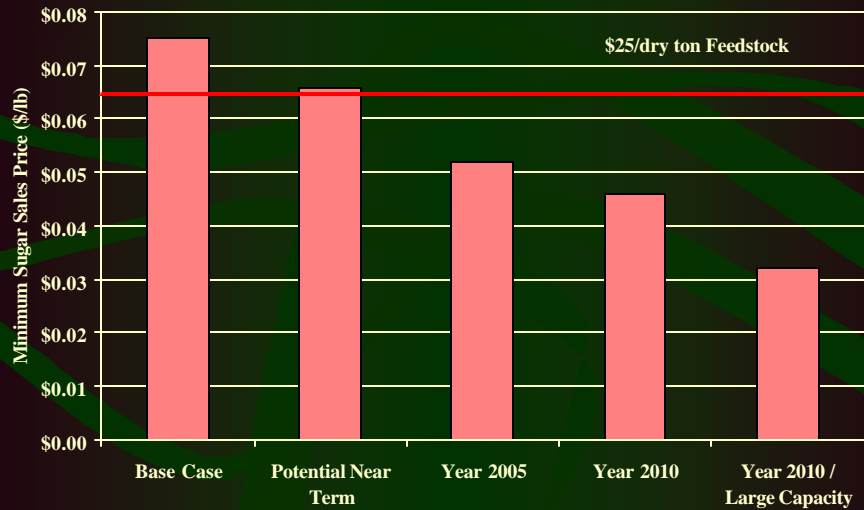
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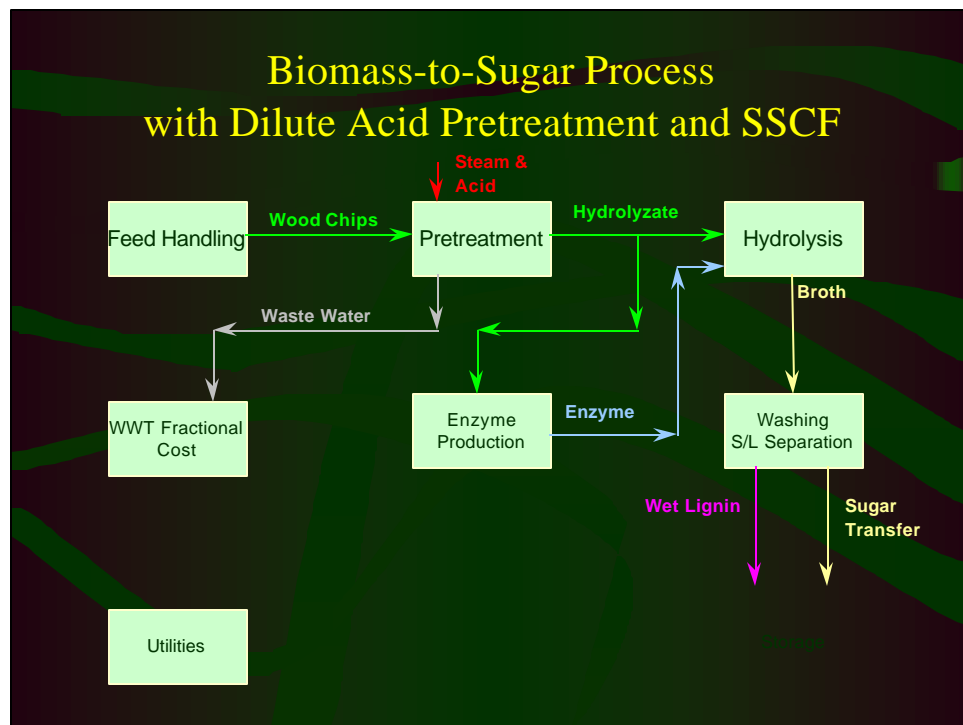
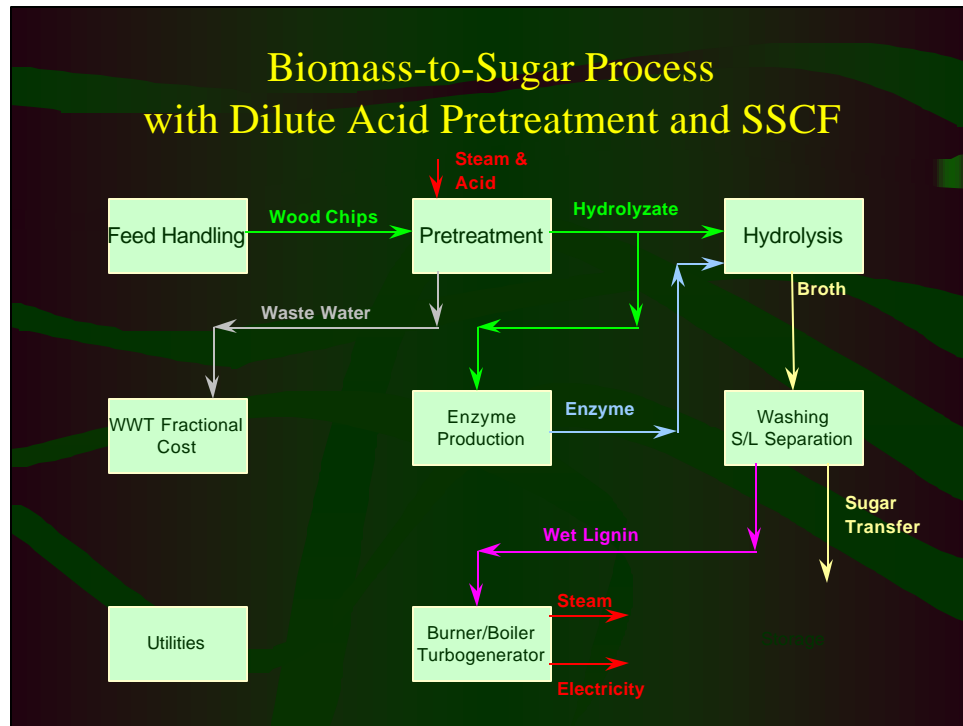


Required Sugar Transfer Prices Combustion of Lignin

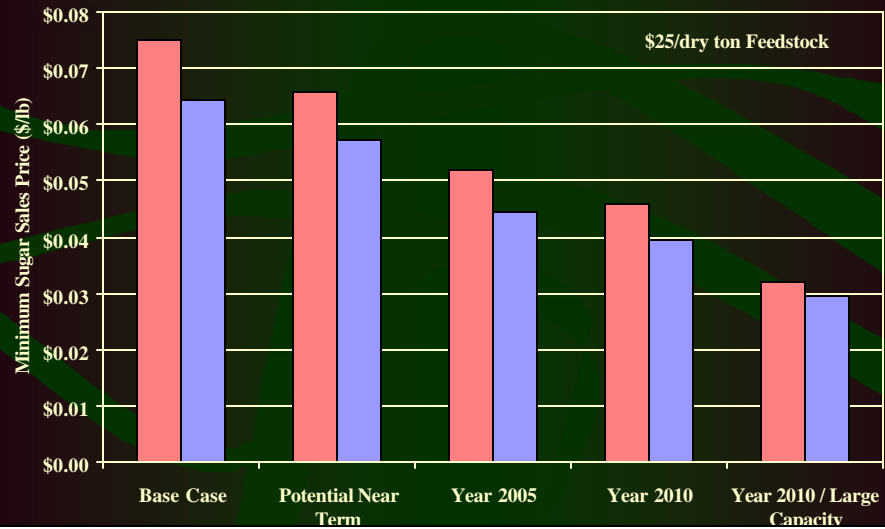


Lignin Processing

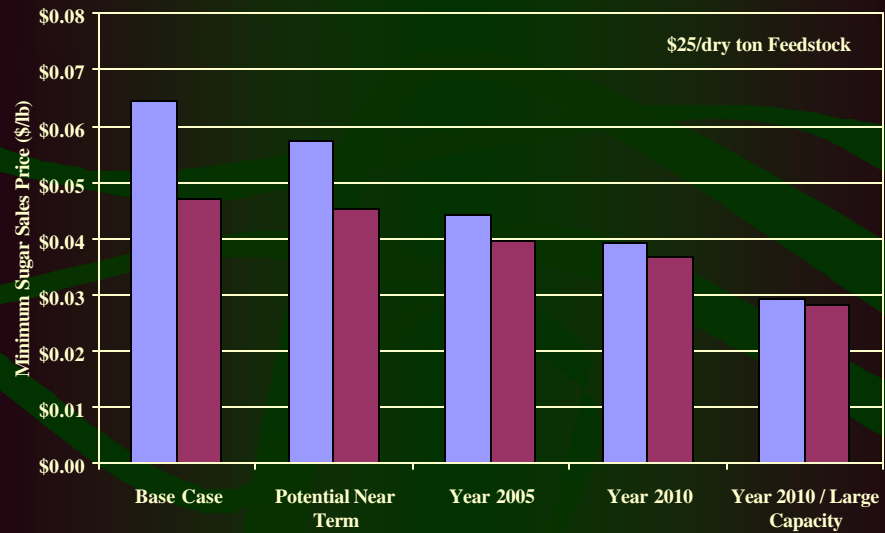
- Burn to Produce Steam and Electricity
- Gasify and Burn to Produce Electricity
- Depolymerize and Hydrotreat to Produce Branched Aromatic Fuel Additives
- Chemically Convert to Fuel Additives
- Chemically Convert to Other Chemicals
- Gasify and Biologically Convert to Other Chemicals



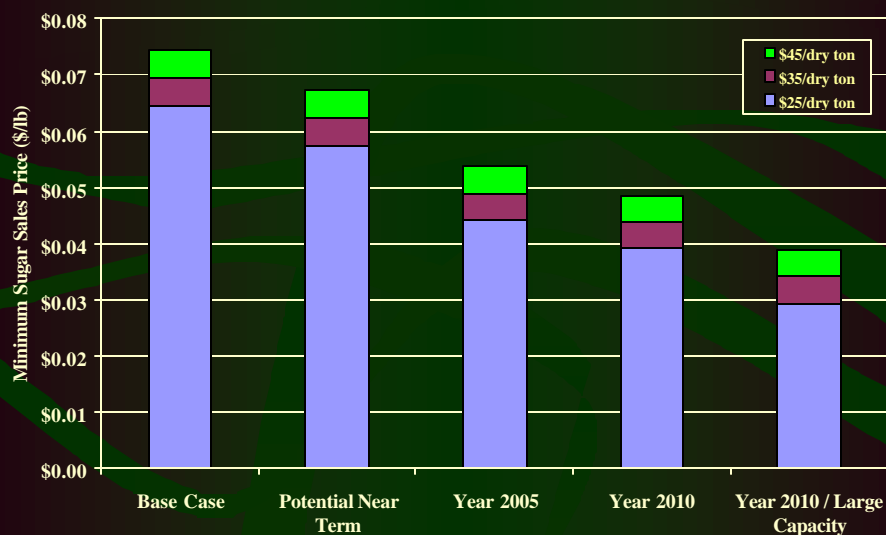
Required Sugar Transfer Prices Sale of Lignin on Constant LHV Basis



Cellulase Enzyme Cost Contribution



Feedstock Cost Effects



Conclusions

- Fermentable Sugar is an Intermediate Product of Biomass-to-Ethanol Processes
- Sugar can be Used as a Feedstock for Bioproduction of Other Chemicals
- Biomass-Sugar may be Capable of Competing with Sugar from Corn ($6\frac{1}{2}\text{¢/lb}$) in the Near Future

